THE VISIBILITY OF AN UNDERWATER DISPLAY AS AFFECTED BY TURBIDITY, DISPLAY BACKGROUND COLOR, AND THE COLOR AND INTENSITY OF ILLUMINATION

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THESIS

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ABSTRACT

The intent of this study was to examine the effects of four environmental factors on a visual reading task in a flooded tank without ambient illumination. The primary reading task was to make an accurate vocal report of a reading on a circular voltmeter under differing conditions of turbidity, display background color, and the color and intensity of illumination.

The principal facet of this research not found in existing literature was that subjects were allowed to set the illumination intensities at the lowest level they subjectively felt was needed without sacrificing accuracy or speed. Because the subjects seemed to adjust the intensities to equalize the effects of other variables, there was a statistical difference in response times only between the two water turbidities. This difference would be of slight consequence in the real world (.07 seconds).

The expected error rate over all variables was .092 errors per trial with no variable having a significant affect over others. Power considerations indicated that a black background illuminated by white light would be a feasible combination.

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I. INTRODUCTION

Underwater vision has been a subject of concern in many sectors of our society. The casual weekend scuba diver, the civilian construction firm and the military frogman have all been keenly interested in how well they can see under varying conditions of the submerged environment. The turbidity or murkiness of the water, depth, object colors, viewing distances, ambient and controlled illumination, contrasting backgrounds and movement are a few of the factors influencing underwater vision which have been examined in the technical literature.

Kinney, Luria and Weitzman (1968) found that color visibility depends on both the type of water involved, i.e. clear or turbid and the kind of illumination employed based on their earlier work concerning transmittance curves and wavelengths (1967). Luria and Kinney (1970) found that both physical and psychological factors act to produce a wide variety of perceptual distortions underwater, particularly that the image of an underwater object is altered in apparent size and distance, the color and brightness of it are changed and its outline becomes less clear under varying conditions of these two factors. Duntley (1963) has provided most of the scientific guidance and optical engineering methods involving light in the sea in a number of articles to include derivations of appropriate formula and fundamental relationships.

Although Beam and Shannon (1967) of North American Aviation Inc. and several British firms have made contributions in the area of military diving, most of the pertinent research has been done at the U. S. Naval Submarine Medical Center at Groton, Conn. All of the previously mentioned literature would have been extremely valuable in the construction

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of instrument displays for the various swimmer delivery vehicles (SDV) constructed by the U. S. Navy in the past. Unfortunately little consideration was placed in the area of human engineering of these vehicles, often resulting in poor dial visibility. In an effort to improve this aspect of the SDV, work has been funded by the Navy Electronics Laboratory (NEL) Human Factors Division, San Diego in conjunction with Professor G. K. Poock of the U. S. Naval Postgraduate School. Of particular importance was the research done by Poock (1972) and Ruckner (1972) which examined the three parameters of turbidity, illumination color and viewing distance. Extensive work was done by Ruckner in constructing a tank and suitable instrumentation to simulate vision in a flooded submersible diving vehicle compartment. This thesis is a continuation of Poock and Ruckner's work with the viewing distance held constant and subject controlled illumination. Its primary objective was to further the state of the art in design of dial instrumentation in the SDV. It must be noted that many variables affecting underwater vision have not yet been extensively studied, and that this effort only examines four under a tightly controlled situation. Hopefully the results will contribute knowledge to more general and less strictly bounded circumstances.

II. EXPERIMENTAL DESIGN AND PROCEDURE

The first three portions of this section deal with the physical aspects of this experiment: the display configuration and meter specifications, the electrical apparatus and measuring methods and a brief description of the subject class. The last two pertain to the analytical aspect: the experimental design and the data gathering and analysis procedure.

A. DISPLAY

The displays used for this study were circular 0-10 volt D. C. voltmeters (Weston Electrical Instrument Corp. Model 301). Two display conditions were used in the experimentation. One display was the actual voltmeter with black lettering on white background. A photographic negative reproduction provided an identical display with white lettering on a black background.

Each instrument was illuminated by a "donut" shaped circular plastic (lucite) ring, (see Appendix E) which was mounted on the front periphery of each meter and used to spread the light evenly from the following bulbs. The lucite ring contained twelve G. E. No. 44 six volt bulbs which were inserted into drilled wells from the outside of the ring and slanted inward toward the meter face. Four equally spaced bulbs were illuminated at any one time to produce white, red, or green illumination on the meter. Green and red illumination were obtained by using Kodak Wratten gelatin filters in front of the respective bulbs used for those colors. The red filter was a Wratten number 29 with dominant wavelength of 632.7 nanometers. The green filter was a Wratten number 61 with dominant wavelength of 533.8 nanometers. (These wratten filters were

chosen to correspond as closely as possible to the colors used in the concurrent work of Miller and Kirtz (1972).) Two identically calibrated meters were used with the exception that one had black lettering on white background and the other vise versa. Each meter could easily be inserted or removed from the circular lucite ring and the desired illumination color on the face of the meter could easily be set to white, red or green by a simple electrical switching arrangement.

The voltmeters had a 90 degree circular scale swept by a pivoting pointer. The descriptive data of the meters are listed below:

1. <u>Number Size</u>

   Book style, with a height of .108", stroke width of .015" or a stroke width to height ratio of 1:7.

2. <u>Indicia Size</u>

   Indicia had a width .017" for the major and .010" for the major indicia and .087" for the minor indicia and .156" major in height.

Brightness of the meter faces was determined by measuring the reflectance of the black and white surfaces being used. The white used on the meters showed a reflectance of 30 percent and the black showed a reflectance of 4 percent using white illumination. The brightness contrast was 86.7 percent and the brightness ratio was approximately 7.5:1.

B. APPARATUS

This study was conducted using E. A. Ruckner's finely constructed wooden testing tank which holds approximately 240 gallons. It is felt that the tank's size (compared to a number of 5 to 10 gallon-size tanks used elsewhere by other investigators) was a definite factor in eliminating or at least normalizing variables which might have had an effect in

the smaller testing environments. The rectangular tank (2' x 2' x 6') was constructed of 3/4" exterior grade plywood. A standard oval face mask was mounted in the center of one end. The tank was calked, sealed with a commercial yacht sealer, and the inside painted black. The entire tank was then mounted on a frame of 2x4 pine with the center of the face mask 48 inches above the floor to allow subjects to be comfortably seated. The tank also had a lid to eliminate ambient illumination (See Appendix C).

The test display which was positioned inside a water tight 1/4" plexiglass box, was mounted in such a way as to be level to the face mask when the box was placed inside the tank. Viewing distance was kept constant at 12". Color illumination was achieved by the previously mentioned "donut" ring.

A shutter was located between the face mask and the display to control the actual time of exposure to the subject (Appendix D). Timing and shutter control were accomplished with a Lafayette Instrument Company Multi Reaction Timer, Model 6302 BX, coupled with a Lafayette Voice Time Control, Model 6602A.

A second identical matching meter face, either black on white or white on black depending on which test display was being used, was located directly above the test display and also respectively color illuminated and mounted in a lucite ring. This second meter was not read by the subject but served to provide the same level of illumination to the subject's eyes during the time the main display was concealed by the shutter. When the shutter opened for the subject to read the display, the top meter lights were automatically turned off. When the subject responded verbally, the shutter closed and the top meter lights came back on so the subject would have a constant level of illumination at all times.

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Turbidity levels in the tank were set at two levels -- clear tap water and a very murky water. Turbidity was achieved by using Nigrosin dye to discolor the tap water. The dye, in crystal form was measured carefully by weight in an attempt to keep the two specific turbidity levels as constant as possible. Turbidity was measured by use of the attenuation coefficient (α) as described by Duntley (1963) and Luria and Kinney (1970). The units of the attenuation coefficient (α) are natural log units per meter. The attenuation coefficient for the different levels of turbidity was converted from the percent transmission measured on a monochromatic spectraphotometer with a 10 centimeter path. Readings were taken to correspond with the spectral characteristics of the Wratten filters. The range of the attenuation coefficient for the clear and murky conditions may be seen in Table 1 which represents the average turbidity for the two spectrums. The spectraphotometer used was a "Spectronic 100" manufactured by Bausch and Lamb.

The illumination levels were controlled by the subjects and set at a level which the subjects felt would be a minimum acceptable level for reading the display without sacrificing speed or accuracy. (See Appendix A: Instruction).

C. SUBJECTS

The subject field consisted of 16 males ranging in age from 22 to 36 years with a mean age of 28.7. Eleven were students at the Naval Postgraduate School, and of the remaining five, three were active military officers, one an engineer and one a graduate student in philosophy. There were no non-swimming subjects and five had extensive diving experience.

TABLE I

RANGE OF ATTENUATION COEFFICIENT (α)

TURBIDITY LEVEL	LOW	Trans*	MEAN	Trans*	HIGH	Trans*
CLEAR	.16	85.1%	.35	70.8%	.50	60.5%
MURKY	5.06	.6%	5.74	.3%	6.31	.2%

* Transmittance is the average transmittance through 1 meter of water for 533.8 and 632.7 nanometers.

None of the subjects wore glasses although two wore contact lenses for 20/20 corrected vision. No subject was color-blind. All subjects were used to reading dials in their related duty positions of aviation, navigation, etc. None had significant breathing difficulties with the face mask.

D. EXPERIMENTAL DESIGN

Twelve conditions of the display (3 illumination colors -- white, red, green - by 2 dial backgrounds -- white and black - by 2 turbidity levels -- clear and murky) were presented to each subject in two forty minute periods separated by approximately fifteen minutes (due to changing the turbidity condition). For approximately 30 minutes before testing and during the testing when displays and other variables had to be changed, all subjects wore red goggles to keep their eyes dark adapted. There were brief breaks in changing environmental conditions and no subjects complained of fatigue. Total testing time per subject averaged approximately 85 minutes. The following aspects form the basis for the test design:

1. All subjects received each of the twelve conditions but in random order. Due to difficulty in changing turbidity level, six conditions were presented in each turbidity level prior to changing that level. Data bias in turbidity was prevented by scheduling 50% of the subjects for the clear level first and conversely.

2. Each subject was tested for 20 trials at each condition. The first 10 were presented as training and learning. The last 10 composed a "data run" on a subject with a total of 1920 data points on all sixteen subjects.

3. Voltage readings to set the display numbers were selected from a table of random numbers uniformly distributed from 0.0 to 10.0.

4. Before trials began in any given condition, subjects adjusted the illumination to a level at which they felt was a minimum without sacrificing speed or accuracy of the meter readings.

5. Response times, errors, and footlamberts of illumination to obtain the adjusted illumination intensity were the criteria on which the four variables (subjects, light illumination color, background color of display, and turbidity of water) were evaluated.

6. Environmental conditions which were held constant were: ambient illumination (total darkness), viewing distance and display size.

E. PROCEDURE

Each subject was shown the tank and the electronic apparatus and then read a set of written instructions (See Appendix A). The experimenter was able to vary the voltmeter readings inside the tank and monitor them on a calibrated voltmeter outside the tank. On the subject's command, the tester varied the display intensity to the lowest level at which the subject could make a reading without sacrificing accuracy or speed. At least four trials were run at each condition per subject to determine stable intensity levels.

During the ten learning trials at each condition, the subject was shown errors and given an opportunity to recheck his response. In some cases subjects were given additional time to become familiar with the testing apparatus when they demonstrated minor breathing difficulties initially.

Response times (hundreths of seconds), intensity levels (volts) and errors were manually recorded by the tester. Knowing the voltage required for a given intensity level, the footlamberts of illumination at the face of the meter could be determined from previously calibrated curves. Also, knowing the transmittance of the various wavelengths in the two turbidities of water, the footlamberts, at the face mask 12 inches away, could be calculated. The actual mathematical conversion was accomplished by using powers of natural logarithms.

III. RESULTS

Response times, errors and intensity levels were the measuring parameters of subject performance. Twenty trials were taken on each subject for a particular combination of conditions. To eliminate learning, the correct responses of the last ten trials were averaged to yield one data point. These data were analyzed with a 2x2x3 repeated measures analysis of variance (ANOVA) by use of the UCLA Bi-Med. computer program. A standard of $p < .05$ was used to determine if a variable was significant.

Table II indicates that the only variable which affected response times significantly was turbidity. The fact that the other variables did not influence response times is not surprising, because subjects chose the lowest level of intensity which would enable them to still make accurate and rapid responses. As such, it was expected that none of the variables would affect response times since the subjects would probably adjust the intensities to an optimal illumination level in each condition.

The mean response time for the clear turbidity condition was 1.16 seconds and 1.09 seconds for the murky condition. See Figure 1. At first glance, the faster response time for the murky condition might seem unusual. However, this is not surprising to the author, because every subject seemed somewhat surprised at how dark the water appeared. Subjectively, the author had the feeling that the subjects seemed to force themselves to try a little harder when looking through the murky turbidity condition. However, it should be pointed out that this discussion has concerned a statistical difference, and the difference of .07 seconds probably would have little significance in the real world.

TABLE II

ANALYSIS OF VARIANCE, RESPONSE TIMES

SOURCE	DF	MS	F	p
SUBJECTS(S)	15	0.905		
TURBIDITY(T)	1	0.257	4.59	.05
BACKGROUND (B)	1	0.0481	2.00	.25
COLOR(C)	2	0.018	1.80	.25
SxT	15	0.056		
SxB	15	0.024		
SxC	30	0.010		
TxB	1	0.005	0.238	NS
TxC	2	0.024	3.000	.10
BxC	2	0.010	1.250	NS
SxTxB	15	0.021		
SxTxC	30	0.008		
SxBxC	30	0.008		
TxBxC	2	0.00006		
SxTxBxC	30	0.006		
TOTAL	191			

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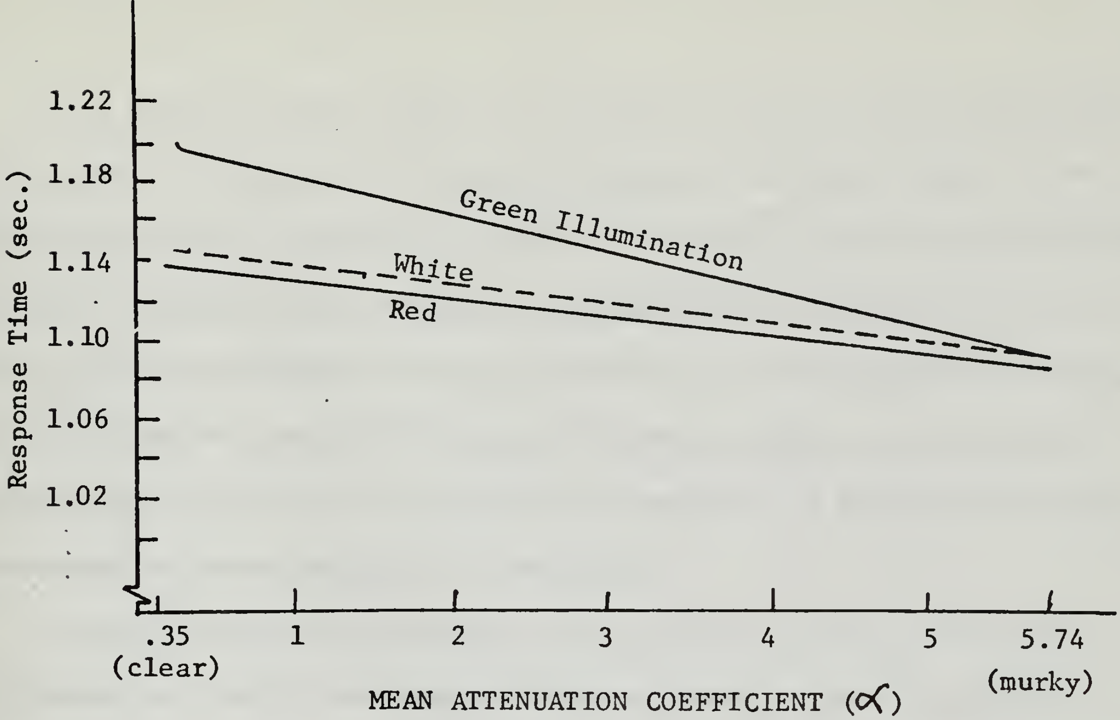


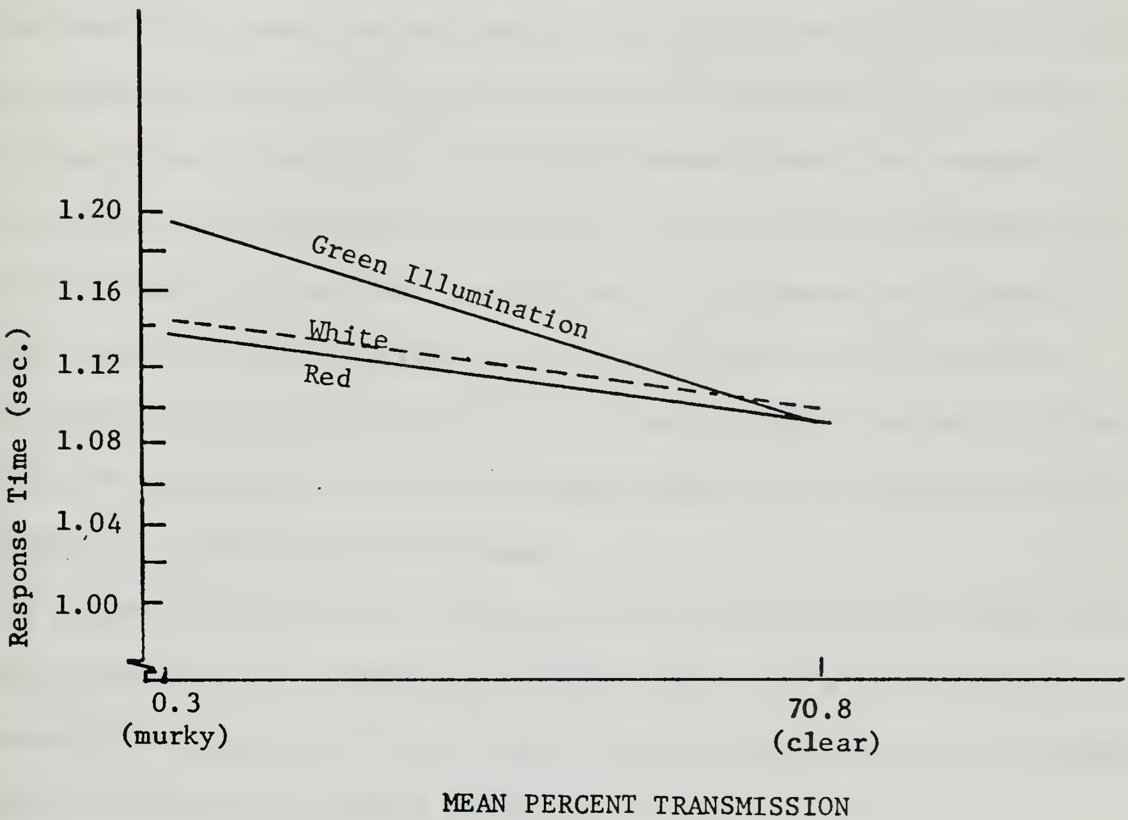


Figure 1. Mean Response Time vs. Mean Attenuation Coefficient and Mean Percent Transmission

The average response time of all conditions was 1.13 seconds which does agree closely with the results of Miller and Kirtz (1972) at NEL probably because an effort was made to standardize experimental conditions. Poock and Ruckner had an average response time of 1.85 seconds but in this latter experiment no effort was made to maintain constant illumination. From the previous discussion of test procedure and noting the photograph in Annex E, the constant illumination in this experiment was expected to reduce subject eye adaptation.

Because the power requirement was of prime concern, the original illumination levels were measured directly next to the display face. Table III shows the results of an analysis on the light levels at the face mask 12 inches from the display. This data was obtained by knowing the constant distance (12 inches) and the transmittance of the water for red and green illumination. For white transmittance, the average of 400, 533.8 and 700 nanometers was used. No significant difference was noted between footlamberts to which subjects adjusted the intensity in the clear and murky turbidity levels. One might conclude from the intensity data in Table III that the intensity levels probably did not cause the difference in response times because the intensities were not found to be significantly different.

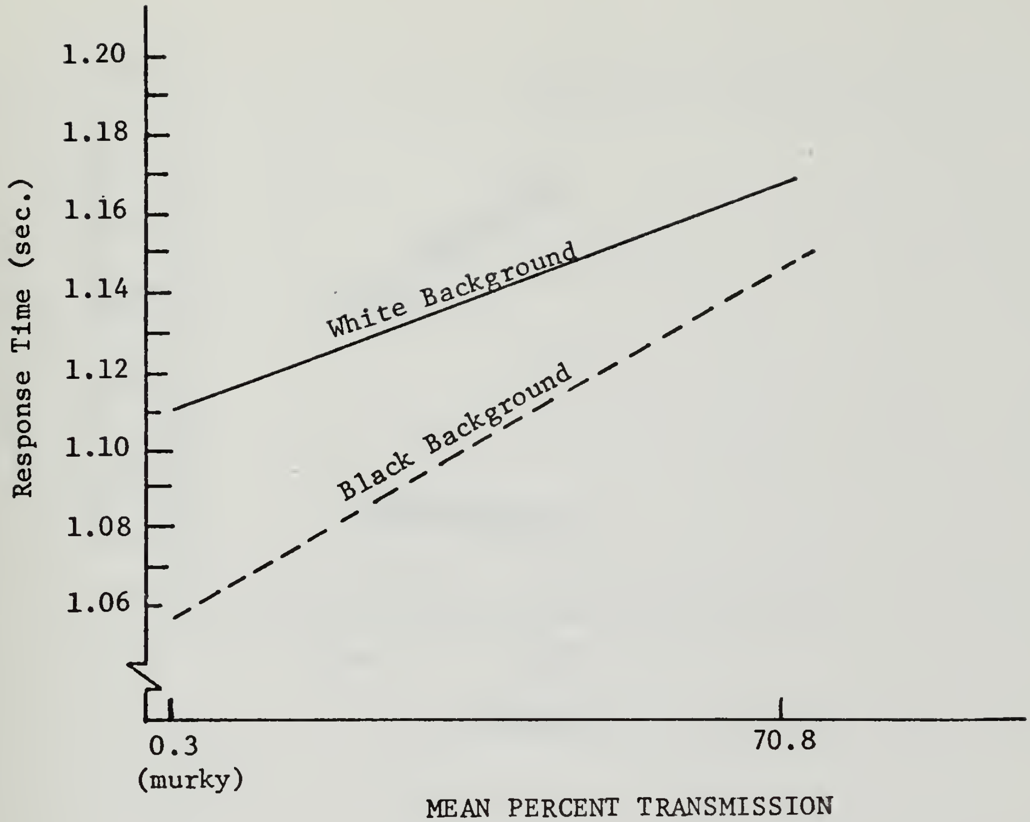
Figure 2 shows that illumination color and background color of the dial display did not influence response times. As might have been expected, the subjects adjusted the intensities so that these variables would not increase response times.

Figure 3 shows that the intensity levels set by the subjects varied greatly for both display background and color of illumination. From Annex B, the white background illumination settings averaged .09, the red .03

TABLE III

ANALYSIS OF VARIANCE, INTENSITY (FOOTLAMBERTS) AT FACE MASK

SOURCE	DF	MS	F	;
SUBJECTS(S)	15	1.00992		
TURBIDITY(T)	1	.00604	2.11	NS
BACKGROUND(B)	1	.21127	54.7	.001
COLOR(C)	2	.06314	19.1	.001
SxT	15	.00286		
SxB	15	.00386		
SxC	30	.00331		
TxB	1	.01619	10.6	.01
TxC	2	.03908	22.6	.001
BxC	2	.03354	16.9	.001
SxTxB	15	.00153		
SxTxC	30	.00173		
SxBxC	30	.00198		
TxBxC	2	.02910		
SxTxBxC	30	.00149		
TOTAL	191			



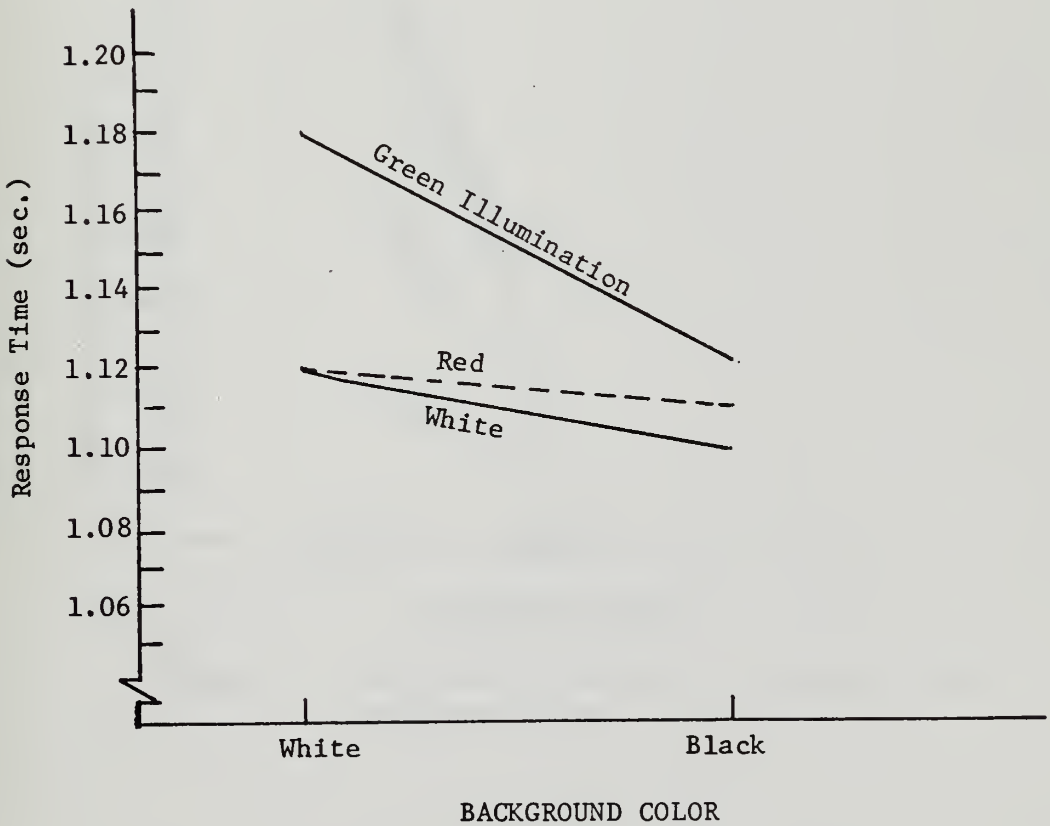


Figure 2. Mean Response Time vs. Mean Percent Transmission and Background Color

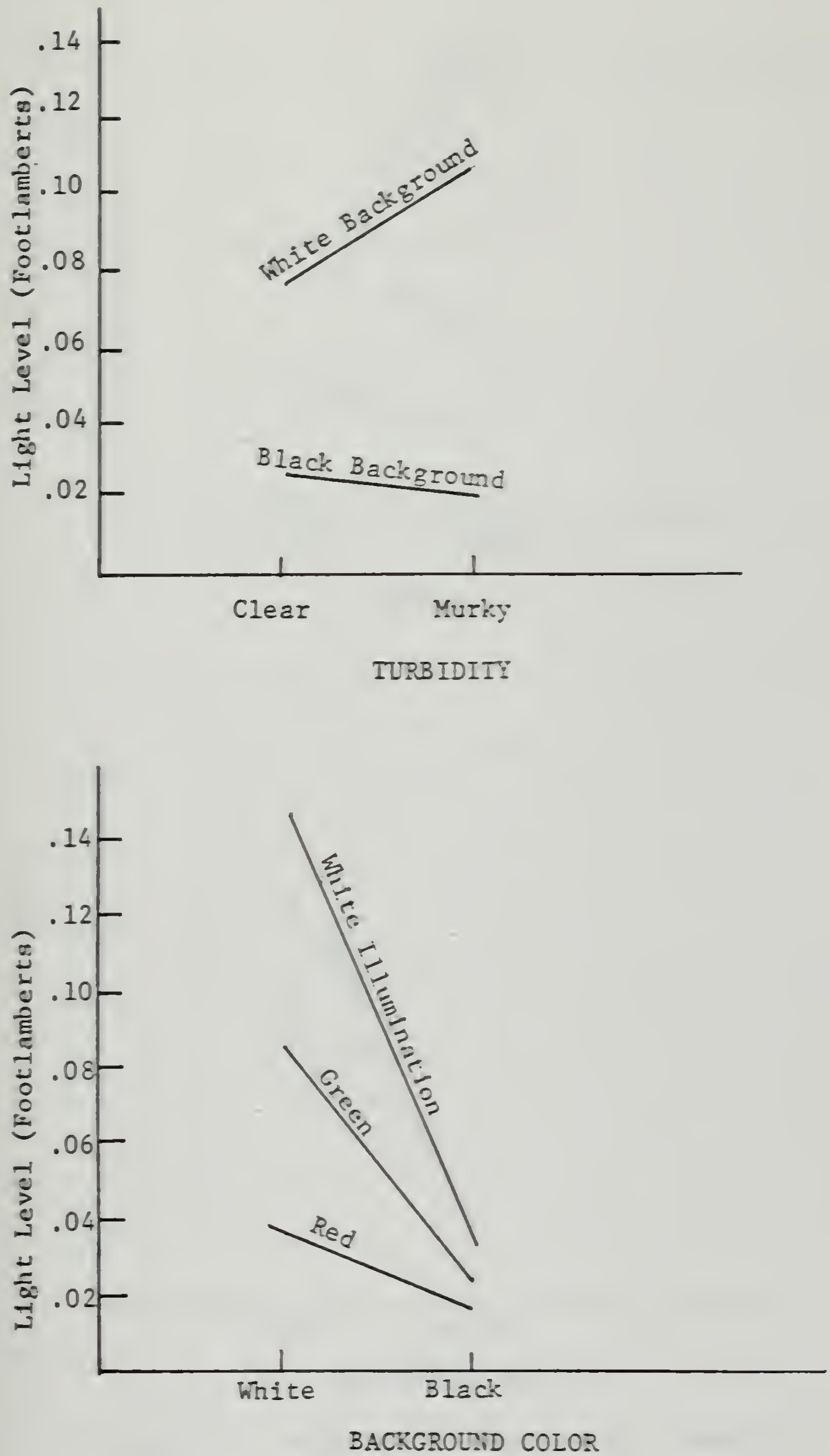


Figure 3. Background Intensity vs. Turbidity and Background Color.

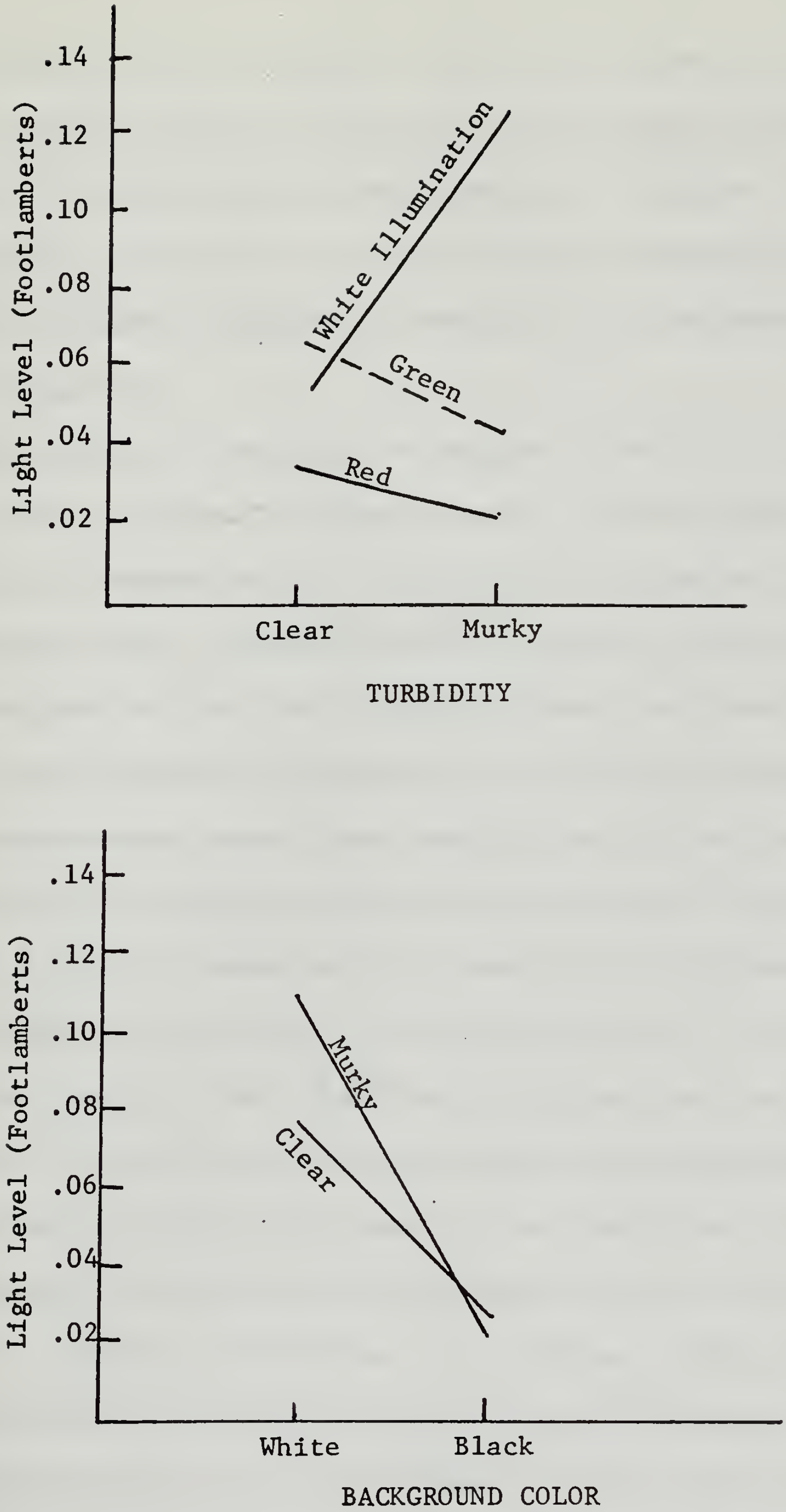


Figure 4. Background Intensity vs. Turbidity and Background Color

and the green .06 footlamberts. All three of these footlambert levels at each of the colors was shown to be significantly different from each other at the .05 level by a Duncan Multiple Range Test. The top drawing of Figure 3 also indicates that for similar response times, the white display background required an average of .07 footlamberts more than the black background.

Considering the two way interactions of Table III, the three significant ones are shown in Figures 3 and 4. Although they are indeed statistical interactions, it is difficult to interpret them in an operational sense. The bottom graph of Figure 4 shows an interaction with subjects setting less footlamberts under the black background for murky water than for clear water but the difference was only .007 footlamberts which seems almost insignificant in the real world. The difference was reversed under the white background condition. The top graph of Figure 4 demonstrates the same type of phenomenon.

The physical electrical configuration using G. E. No. 44 bulbs and parallel wiring in the "donut" lucite ring has been explained. The power required for equivalent intensity levels for this experiment and that of Miller and Kirtz (NEL 1972) appear to be comparable. The bulbs draw approximately .25 amps when fully warmed up at 6.3 volts as per advice given by electronic technicians. The average voltage level in this experiment was 2.94 volts to run the color illumination. Therefore, the average power required was .345 watts ($P = I^2R$) since the resistance of the bulbs is 25.2 ohms. The G. E. No. 387 bulb of Miller and Kirtz draws .04 amps when fully warmed up at 28 volts. Their average voltage needed was 15.8 volts with a resulting power requirement of .364 watts since the G. E. No. 387 has a resistance of 700 ohms. The average power for these

two different display configurations were very close, but it is anticipated that with the advancement in design of power output, that the human engineering aspects of visibility, speed and accuracy will be of more importance.

As mentioned, twenty trials were taken per condition with the last ten being considered for analysis. To determine if learning occurred, a "t" test was run between the first ten trials and the second set of ten trials. Specific cases in which the experimenter appeared to notice marked improvement in a subjects performance were chosen. Eight of the most extreme runs were analyzed with no significan difference in the means of the first or second sets of trials thus implying no learning effect. Although this might have been particular only to technique and physical configuration of this experiment, learning can probably be discounted in future work of this type.

A non-parametric study was conducted on the error rate between any levels of the experimental variables. Since the tester had a calibrated deal outside the tank with which to check the subject's response, it was possible to manually record errors during the progress of a run. A response was counted as an error whenever the deviation from the oral response and the correct reading was greater than .2 volts. It was felt that any deviation less than .2 might have been caused by either subjects head or eye movement or the precision of calibration between the monitor and display meters. The calibration was continually checked with considerable difference noted. The analysis indicated no significant difference in the error rates.

Most subjects made very few if any errors and as such the individual distribution of errors in Table IV cannot be considered normally distributed. As a result, the error data in Table IV was analyzed by a chi-square test and none of the experimental parameters exhibited an influence on the error rate. Thus, as in Poock and Ruckner (1972), no variables had a greater or lesser effect on the error rate which was .092 errors per trial. This rate was approximately 2.5 times larger than Poock and Ruckner's earlier results but there are probably many factors which could have caused this difference. These rates can be compared subjectively with those of Miller and Kirtz (1972) in which their average error rate was .12 errors per trial. These are all in the same general realm and can begin to give the designer an idea that one might expect error rates somewhere from three to twelve percent under similar conditions. Figure 5 graphically represents the error rates of this experiment.

TABLE IV

TOTAL ERRORS OVER .2 VOLTS

TURBIDITY	COLOR →	WHITE	RED	GREEN
	CLEAR	23	25	37
	TURBID	32	26	34

DIAL BACKGROUND	COLOR →	WHITE	RED	GREEN
	WHITE	22	25	36
	BLACK	33	26	35

DIAL BACKGROUND	TURBIDITY →	CLEAR	TURBID
	WHITE	40	43
	BLACK	45	49

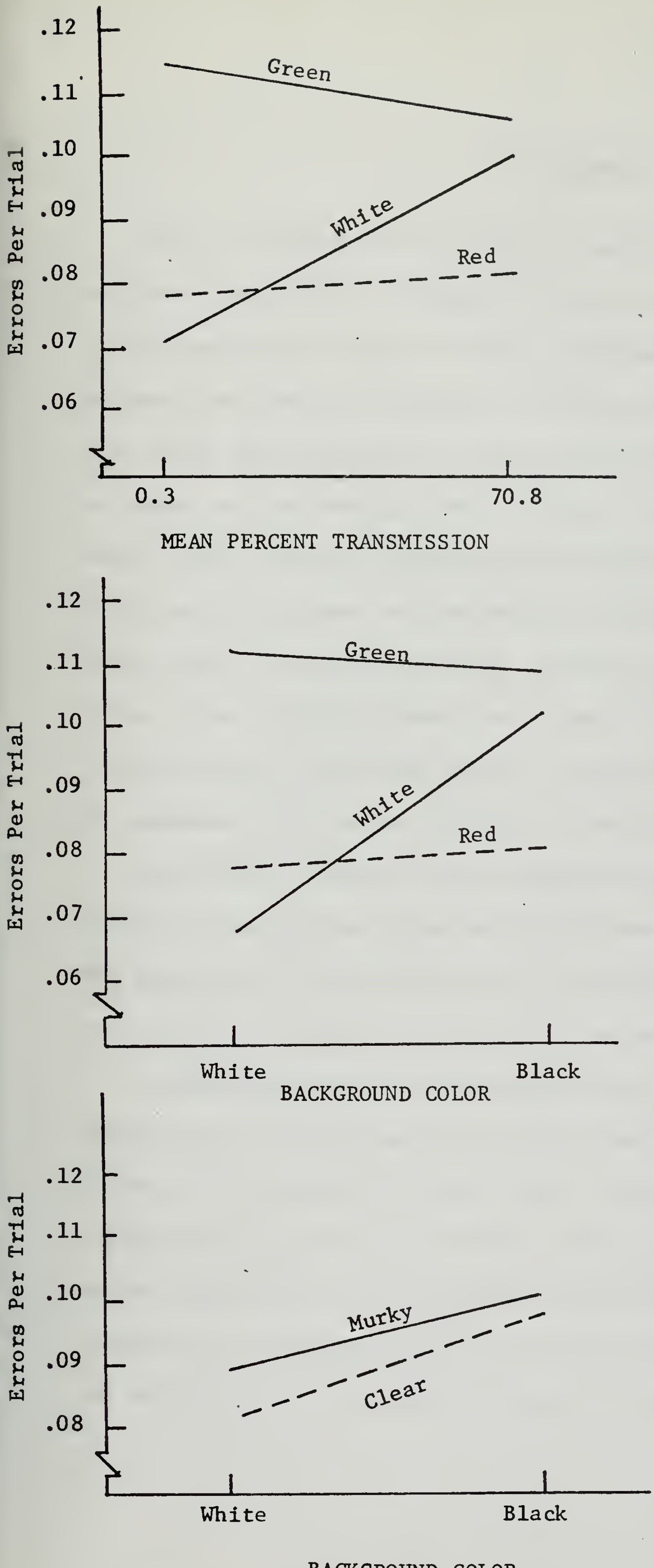


Figure 5. Error Rate Graphs

IV. SUMMARY

Prior to initiating this study, a search of the available literature was made with negative findings, to determine if subjects were allowed to vary parameter levels in similar experiments. It appears that by allowing the subject to adjust the illumination intensity in this study, that other variables such as dial background and illumination color had no affect on the reading task. Although turbidity did appear to have a slight affect that was apparently not normalized by adjustment of intensity, the author made the observation that subjects seemed to concentrate harder under the murky condition. There was a possible psychological affect since turbidity levels were changed only once and the contrast between the two levels was extreme, perhaps causing subjects to attempt to compensate for the more difficult viewing condition.

Essentially response times remained nearly constant under all conditions except the .07 seconds difference between the turbidity levels. The magnitude of this difference to a scuba diver or SDV operator would not appear to be significant in daily operations.

As emphasized in the instructions given to the subjects, power requirements for instrumentation were to be kept to a minimum. White illumination required the least power, .238 watts, followed by red at .363 watts and green at .445 watts. Since response times were similar, white light should be used against a black background because this combination would best meet the dual objectives of underwater readability and minimization of the required power to illuminate the dial display.

Because of the normalizing effects of subject adjusted intensity, no specific comparisons can be made with other experiments although the results do generally agree with the observations of Duntley and more specifically with the literature published by the U. S. Submarine Medical Center.

APPENDIX A

INSTRUCTIONS TO SUBJECTS

You are a subject in an experiment to test your responses to a visual underwater stimulus. There will be differing environmental conditions of the murkiness of the water, background of the instrument face and the light color illuminating the dial.

Assume a comfortable sitting position with your eyes and nose in the face mask. No light should leak around your face and you will have to breathe through your mouth. Should you have difficulty doing this, a nose clip is available. If the face mask becomes fogged at any time, notify the tester immediately.

In front of you, notice the grey plastic shutter directly in the center of the mask at eye level and an illuminated non-functioning dial face to the uper left corner of the face mask. When the shutter is released, you will observe a functioning circular voltmeter at the same illumination intensity as the non-functioning meter which can no longer be seen.

The first task is to adjust the illumination of the voltmeter. As the source which supplies voltage to light the meter also supports other important components in the system, it is imperative to limit the illuminating voltage as much as possible without sacrificing your speed or accuracy in reading the meter. The tester will adjust the illumination at your command. Initially, the light will be extremely bright and then be lowered until you command "stop" at the lowest level you can read accurately. Several adjustments will be made from bright to dim and

conversely until a stable illumination level is obtained. For fine adjustments, you should instruct the tester to go "up" or "down" until you are satisfied. This procedure will be repeated when any of the environmental conditions are changed and it is extremely important to correctly adjust the illumination so as not to impair your performance.

Your primary task is to correctly read the meter and give a verbal response of what you saw. Your response will trigger the shutter via the microphone and electrical circuit. The word "top" has been found to be especially suitable as an initial triggering command. A typical response might be: "Top., 5.4".

Avoid coughing, thinking out loud, or making any other noise which will cause the shutter to close before you are ready. Do not remove your face from the mask until told to do so. Work as quickly as possible but try to make your response accurate. Notify the tester immediately of any difficulties you encounter, or if any of the testing procedures are confusing to you.

APPENDIX B

MEAN DATA FOR RESPONSE TIMES (SEC.)

		TURBIDITY			
		CLEAR		MURKY	
DIAL BACKGROUND →		WHITE	BLACK	WHITE	BLACK
COLOR	WHITE	1.15	1.14	1.10	1.08
of	RED	1.15	1.13	1.10	1.07
ILLUMINATION	GREEN	1.23	1.18	1.12	1.05

MEAN DATA FOR ILLUMINATION AT THE FACE MASK (FOOTLAMBERTS)

		TURBIDITY			
		CLEAR		MURKY	
DIAL BACKGROUND →		WHITE	BLACK	WHITE	BLACK
COLOR	WHITE	.080	.038	.215	.034
of	RED	.045	.022	.033	.012
ILLUMINATION	GREEN	.104	.030	.070	.017

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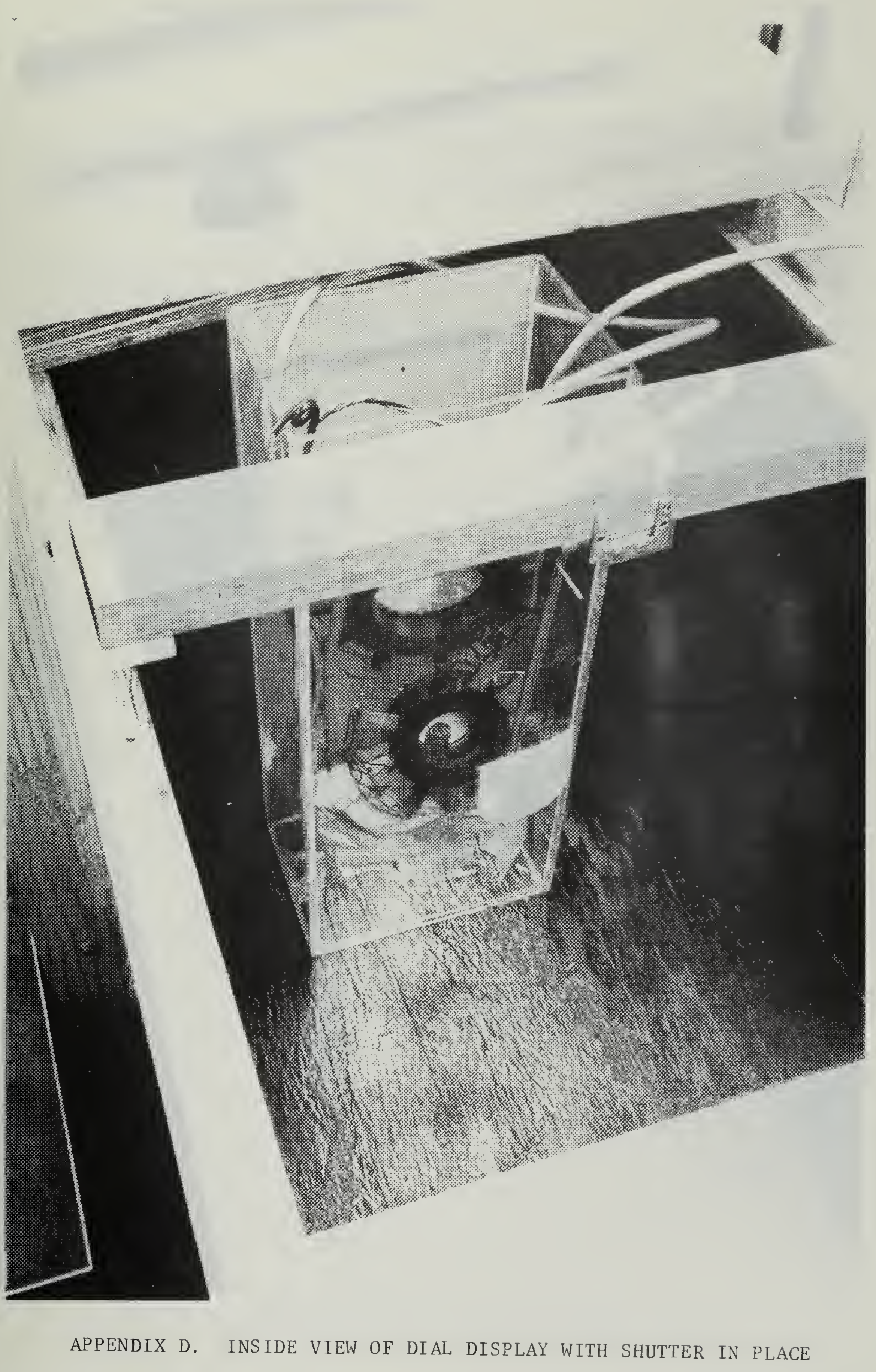
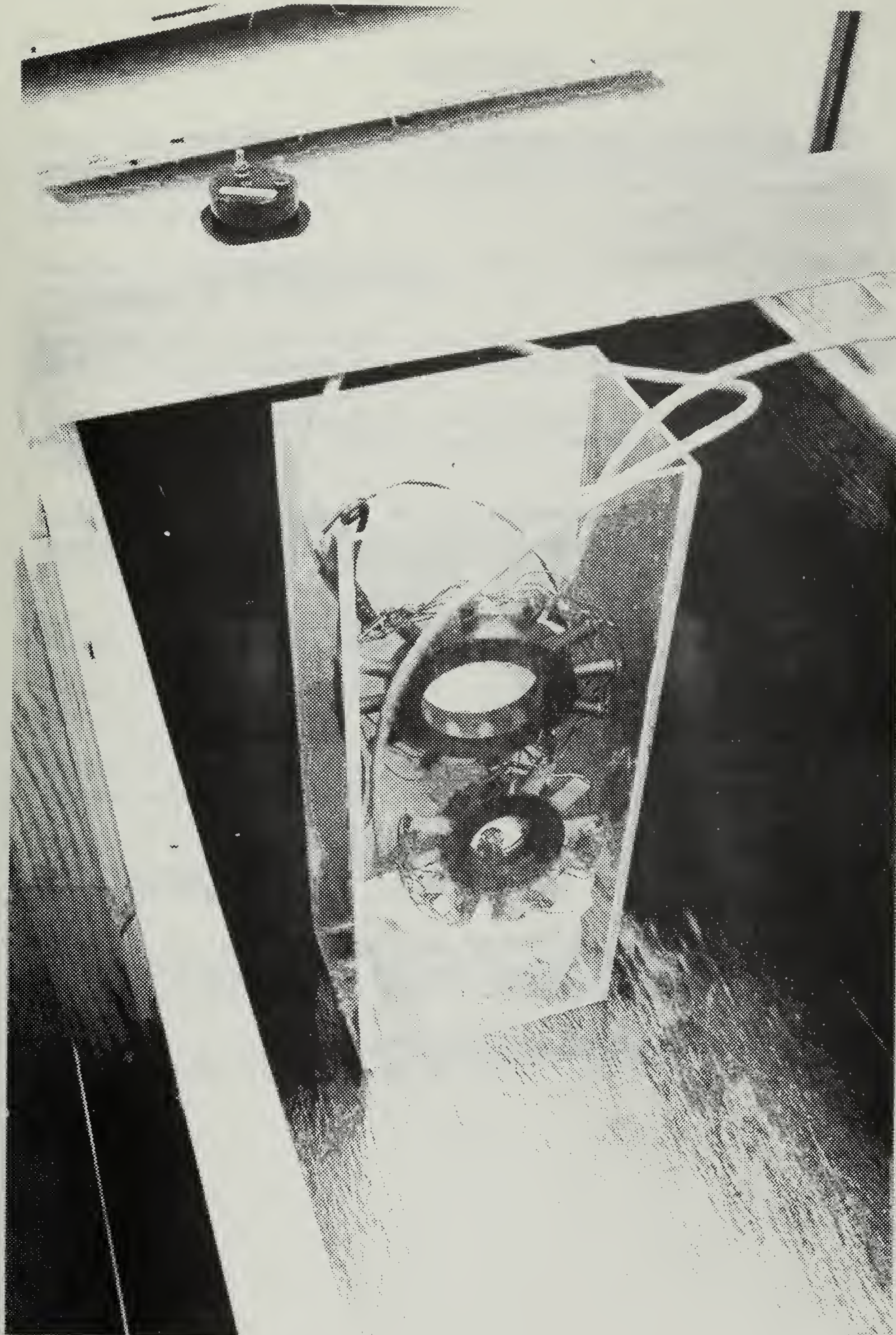
APPENDIX C. OUTSIDE VIEW OF TESTING TANK AND ELECTRICAL APPARATUS



APPENDIX D. INSIDE VIEW OF DIAL DISPLAY WITH SHUTTER IN PLACE



APPENDIX E. INSIDE VIEW OF DIAL DISPLAY WITHOUT SHUTTER IN PLACE

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13. ABSTRACT

The intent of this study was to examine the effects of four environmental factors on a visual reading task in a flooded tank without ambient illumination. The primary reading task was to make an accurate vocal report of a reading on a circular voltmeter under differing conditions of turbidity, display background color, and the color and intensity of illumination.

The principal facet of this research not found in existing literature was that subjects were allowed to set the illumination intensities at the lowest level they subjectively felt was needed without sacrificing accuracy or speed. Because the subjects seemed to adjust the intensities to equalize the effects of other variables, there was a statistical difference in response times only between the two water turbidities. This difference would be of slight consequence in the real world (.07 seconds).

The expected error rate over all variables was .092 errors per trial with no variable having a significant affect over others. Power considerations indicated that a black background illuminated by white light would be a feasible combination.

14. KEY WORDS	LINK A		LINK B		LINK C	
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